Hypobaric Storage of Mature-Green Tomatoes

Marketing Research Report No. 842

Agricultural Research Service
U.S. DEPARTMENT OF AGRICULTURE

Acknowledgments

Among coworkers in the Market Quality Research Division, special acknowledgment is due R. E. Hardenburg and P. H. Heinze for their help with various aspects of the study; Chester S. Parsons assisted with the comparative photography; John T. Worthington did the basic work on the internal color measurements of the test fruits; and H. Carl Vaught helped sort several thousand tomato fruits to obtain satisfactory samples for these tests. James D. Rowan and Harold A. Kramer, of this Division, and Webster Capps, of the National Bureau of Standards, supplied engineering stress data and test materials basic to design of the hypobaric equipment.

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Washington, D.C. Issued August 1969

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 – Price 15 cents

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Summary

Hypobaric storage, or refrigerated storage at less than normal atmospheric pressure, of horticultural produce may have advantages over refrigerated storages now in use. Many principles required for hypobaric storage are yet to be defined. Some of these are discussed and some suggestions are made for the development of others. A design of basic research equipment is presented.

Hypobaric storage is another possible means of obtaining a controlled atmosphere low in oxygen. The lowest pressure tested (180–190 mm. of Hg) retarded fruit ripening the most when the oxygen partial pressure also was reduced. When oxygen pressures were held constant, different levels of total hypobaric pressure caused little if any difference in retardation. The retardation of ripening and color development of mature-green tomatoes may be more directly related to oxygen levels than to levels of total pressure and reductions of ethylene. Gas dilution rates may need to be defined for each kind of produce to be stored. Providing controlled relative humidities is stressed. Some possibilities for hypobaric storage applications are presented for consideration.

Introduction

It has been known for many years that the ripening of fruits is associated with their production of ethylene in the presence of an adequate oxygen supply. Most of the pertinent literature has been reviewed by Burg (*5*).[1] When either oxygen or ethylene is reduced in fruit storage, ripening is usually delayed, and the marketable life of the produce is subsequently extended. Apples are now stored for extended periods in controlled or modified atmospheres, and promising experimental results with other kinds of produce have been published. Among the many methods of producing such modified atmospheres, the hypobaric storage [2] of produce has been considered.

Various aspects of this kind of storage have been investigated. In 1957 Workman and associates (*33*) noted a trivial reduction in the respiration of tomato fruits when the surrounding storage pressure was increased 120 cm. of water.[3] Also, in 1957 Hummel and Stoddard (*20*) reported increases of 20 to 92 percent in the life of several kinds of produce stored in a home-type refrigerator with a compartment maintained at a pressure between 658 and 709 mm. of Hg. Burg and Burg (*6*) reported similar success with additional kinds of fruits and vegetables stored at pressures from 125 to 360 mm. of Hg and in air. They suggested that intercellular ethylene in fruits, prior to respiratory climacterics, rises to levels that stimulate ripening, and if this ethylene is removed, ripening is delayed.

Hypobaric storage of produce conceivably may involve several principles and considerations presently unevaluated. The purpose of this study was to survey some of them and to determine problems that might arise in any commercial adaptations of the method.

Materials and Methods

Equipment

The apparatus for these tests consisted essentially of four 19-liter high-strength steel drums, in which produce was placed and subjected to controlled flows of gases under regulated hypobaric pressures. Figure 1 (top) shows schematically how these flows and pressures were accomplished, regulated, and in part recorded for each drum. Most of this equipment was used during all tests, but not all parts were used at all times. Its general

[1] Italic numbers in parentheses refer to Literature Cited, p. 8.

[2] In this report, "hypobaric storage" means refrigerated storage of produce under gas pressures totaling less than 760 mm. of mercury (Hg) at storage temperature and location without further corrections.

[3] About 88 mm. of Hg at 20° C.

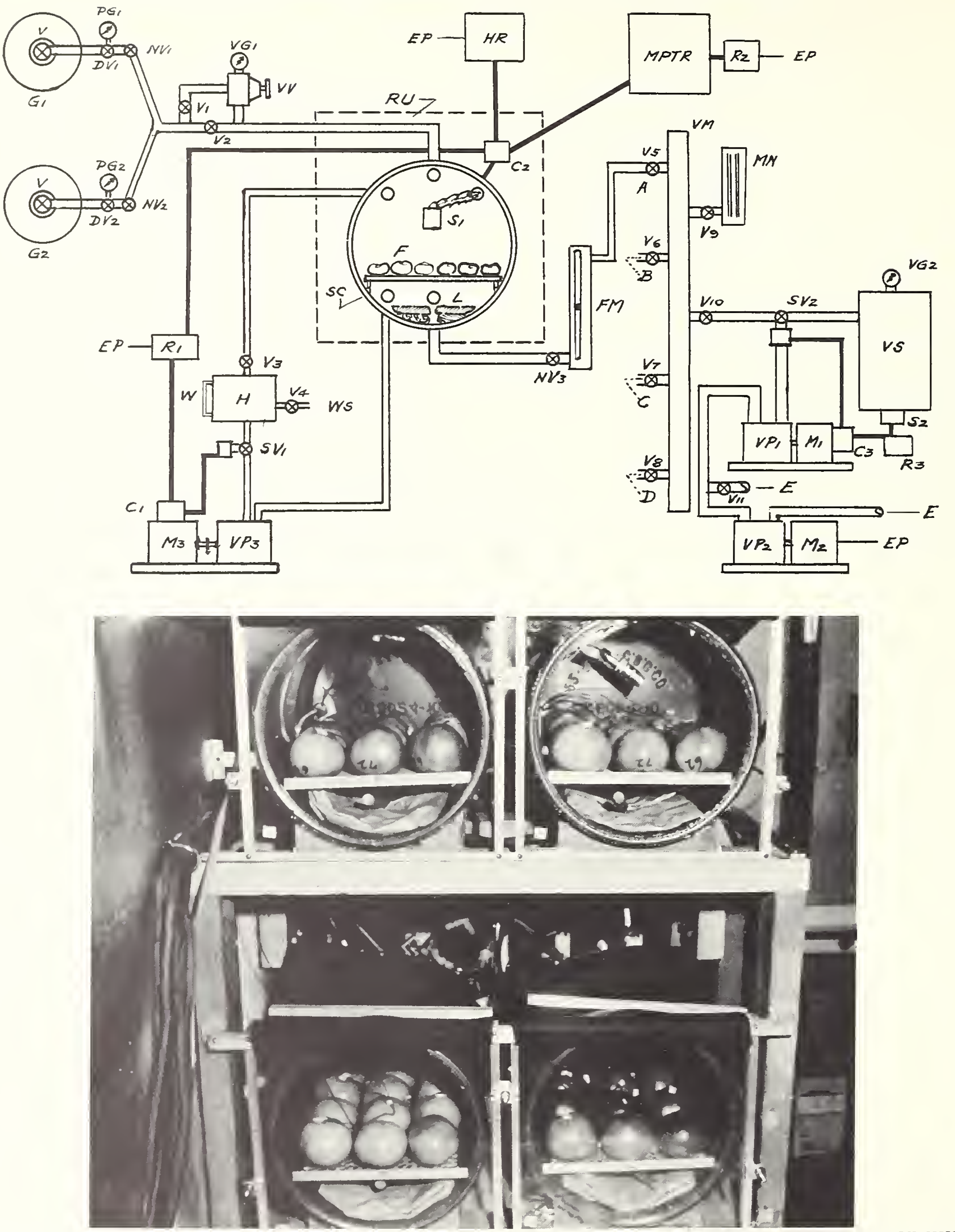

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FIGURE 1.—*Top*, schematic diagram of basic unit of hypobaric storage equipment with auxiliaries. Four such units were used in these tests. See text for identification of principal parts. *Bottom*, arrangement of tomatoes in hypobaric chambers during tests. Thermocouples were attached to fruit surfaces with tape. White dots about chamber rims were beads of moisture. Ends were closed with heavy plastic transparent plates.

operation was automated as much as proposed research objectives permitted (*9, 14, 26, 28, 30*).

The gases (G) for each treatment were commercially obtained in lots of two 200-cubic foot tanks. To prevent shutdowns, these duplicate tanks were regulated in such a way that their supplies automatically were used consecutively. Vacuum valves (VV)[4] automatically maintained the manually adjusted pressure chosen for each treatment. An equal gas flow rate for all pressures was obtained by a needle valve (NV_3) upstream to the calibrated flowmeter (FM) for each treatment. A manifold (VM), with an indicating manometer (MN), aided in maintaining an equal downstream pressure for each treatment (as A, B, C, D) by a pressure-regulated vacuum system (VP_1, VP_2) and its auxiliary equipment.

Both paramagnetic and gas chromatographic analyses were made of the commercially purchased gases used in these tests. (See *13*, *25*.) The differences in oxygen content between that requested and that supplied varied from -3.3 to $+4.1$ percent of the requested amount. None of the supply tanks contained detectable amounts of ethylene. None contained carbon dioxide, although hydrated lime packets (L) were used in all drums as a supplementary aid in removing possible accumulations of carbon dioxide due to a faulty gas sweep.

Humidifying equipment (H), actuated by a suitably selected sensor (S_1) and a humistat (R_1),[5] was available as diagramed. A humidity recorder (HR) was sometimes intraconnected to the drum sensors (S_1). Temperatures in each treatment, sensed by four thermocouples attached to fruit surfaces (fig. 1, bottom), were relayed (R_2) each 3 hours to a multipoint potentiometric recorder[6] ($MPTR$). Other thermocouples about the periphery of each drum sensed the ambient storage temperature (RU). All equipment, except the booster pump (VP_2), was enclosed in a refrigerated storage room.

[4] Matheson Scientific Co., model 49.
[5] S_1 and R_1 are products of Hygrodynamics, Inc.
[6] Brown-Honeywell, Electronik 16 model, 24-point.

Tomato Selection and Experimental Treatments

The initial crop chosen to test this equipment for hypobaric storage was mature-green tomatoes grown in Pennsylvania. They were selected for weight uniformity, symmetry of form, and absence of apparent mechanical and pathological injury. These criteria required the inspection of hundreds of fruits for each replication in order to obtain practically identical test samples. This careful preselection to reduce extraneous variability was considered essential because of the limited lot size (12 fruits) that could be accommodated in the test chamber for any treatment (fig. 1, bottom).

These tomatoes were then further selected as closely as possible for equal maturity by use of a multiple wavelength difference meter (fig. 2). This was a four-filter meter, similar in construction to the two-filter instrument described by Birth and Norris (*4*). Filter selections and the interpretative method essentially were adapted from those used by Worthington and Yeatman (*34*).

After preliminary scanning tests to obtain parameters, two replications were run of the treatments in both series given in table 1. In each series the hypobaric pressure was varied among treatments to four levels. In the first series the percent of oxygen was kept constant in all four treatments, which gave different oxygen partial pressures among treatments. In the second series the oxygen partial pressures were held constant for all treatments and the hypobaric pressures were adjusted to approximate those in the first series.

The tomatoes in each treatment were compared at the termination of each test both photographically and by the difference meter.

TABLE 1.—*Experimental hypobaric pressures and atmospheres at which tomatoes were stored at 65°±3° F. in test series I and II*[1]

Treatment	Series I			Series II		
	Total hypobaric pressure	Oxygen in sweep gas	Oxygen partial pressure	Total hypobaric pressure	Oxygen in sweep gas	Oxygen partial pressure
	Mm. Hg	*Percent*	*Mm. Hg*	*Mm. Hg*	*Percent*	*Mm. Hg*
C	755	21	159	755	5	38
B	570	21	120	545	7	38
A	380	21	80	380	10	38
D	190	21	40	180	21	38

[1] Pressures are to nearest millimeter of mercury at storage temperature. Sweep gas was oxygen in nitrogen to nearest whole percent.

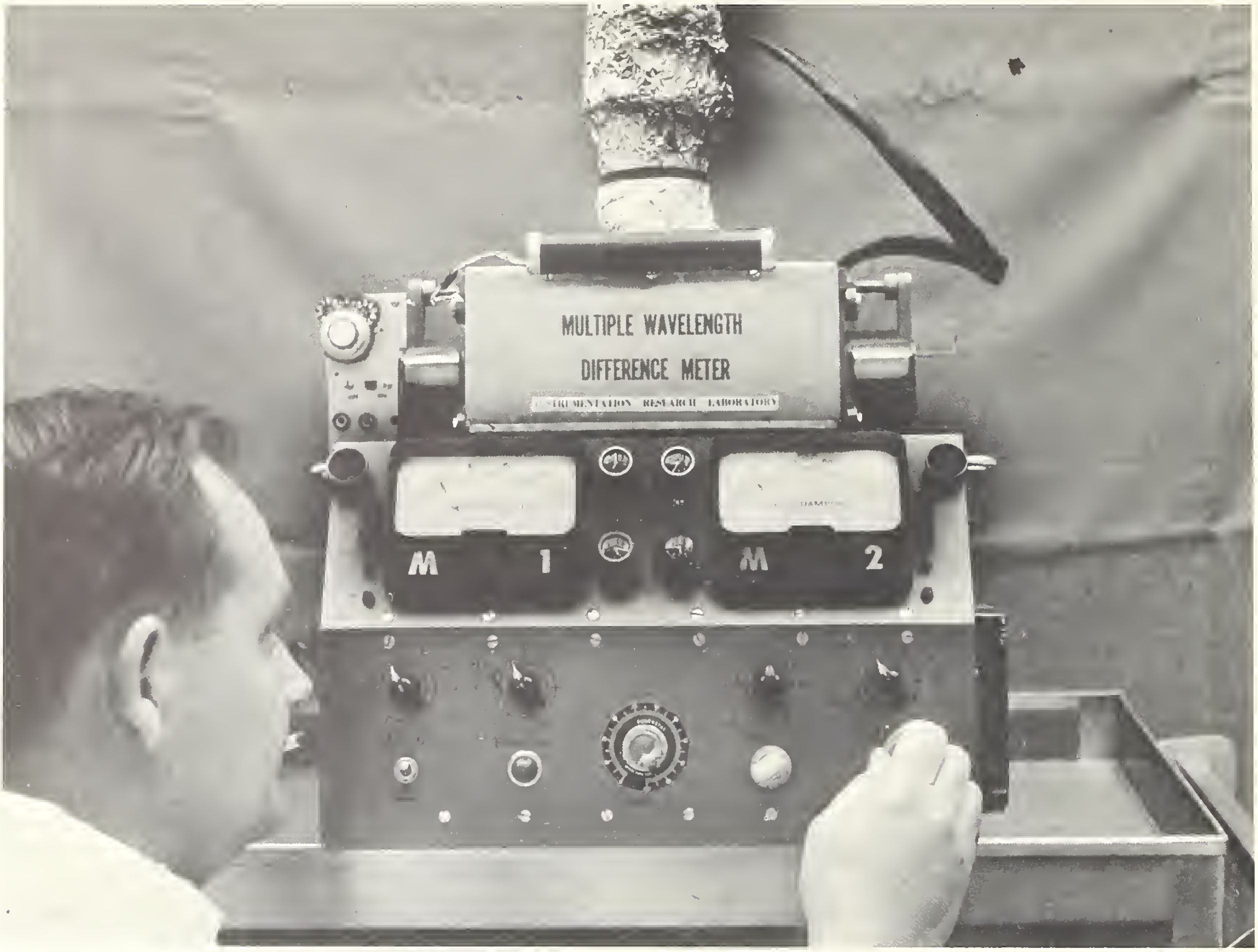

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FIGURE 2.—Multiple wavelength difference meter for indicating probable internal maturity of test tomatoes before and after treatments.

Results

After storage under normal and hypobaric pressures the tomatoes were taste sampled by several staff workers and housewives. The flavor of the ripened fruits in both series was, without exception, normal and acceptable.

Series I Tests

The pretreatment tomato fruits in the series I tests averaged 182 grams each, with a coefficient of variation for weight of only 3.8 percent within treatments and a zero coefficient among treatment means. The pretreatment maturity scores of these fruits had coefficients of variation ranging from 0.3 to 0.9 percent and, again, zero variation among treatment means. The good uniformity of the pretreatment lots is shown in figure 3 (top).

The posttreatment maturity and appearance of the fruits in series I after 12 days at the treatments given in table 1 are relatively apparent in figure 3 (bottom). The darker fruits are redder. Internal color scores, indicated by the difference meter, showed more advanced color development in treatments C, B, A, D, in that order. Ripening was most advanced in treatment C held at the hypobaric pressure of 755 mm. of Hg and most retarded in treatment D held at 190 mm. of Hg. Treatment D also had the lowest oxygen partial pressure (table 1).

Reflectance measurements of these fruits after 12 days at 65° F. were made on a Gardner automatic color difference meter. These measurements as $\tan^{-1}a/b$ scores were as follows for the treatments: C, 63.3; B, 45.2; A, 38.4; and D, 29. After holding the fruits 3 additional days at 70° outside the chambers, these respective measurements had

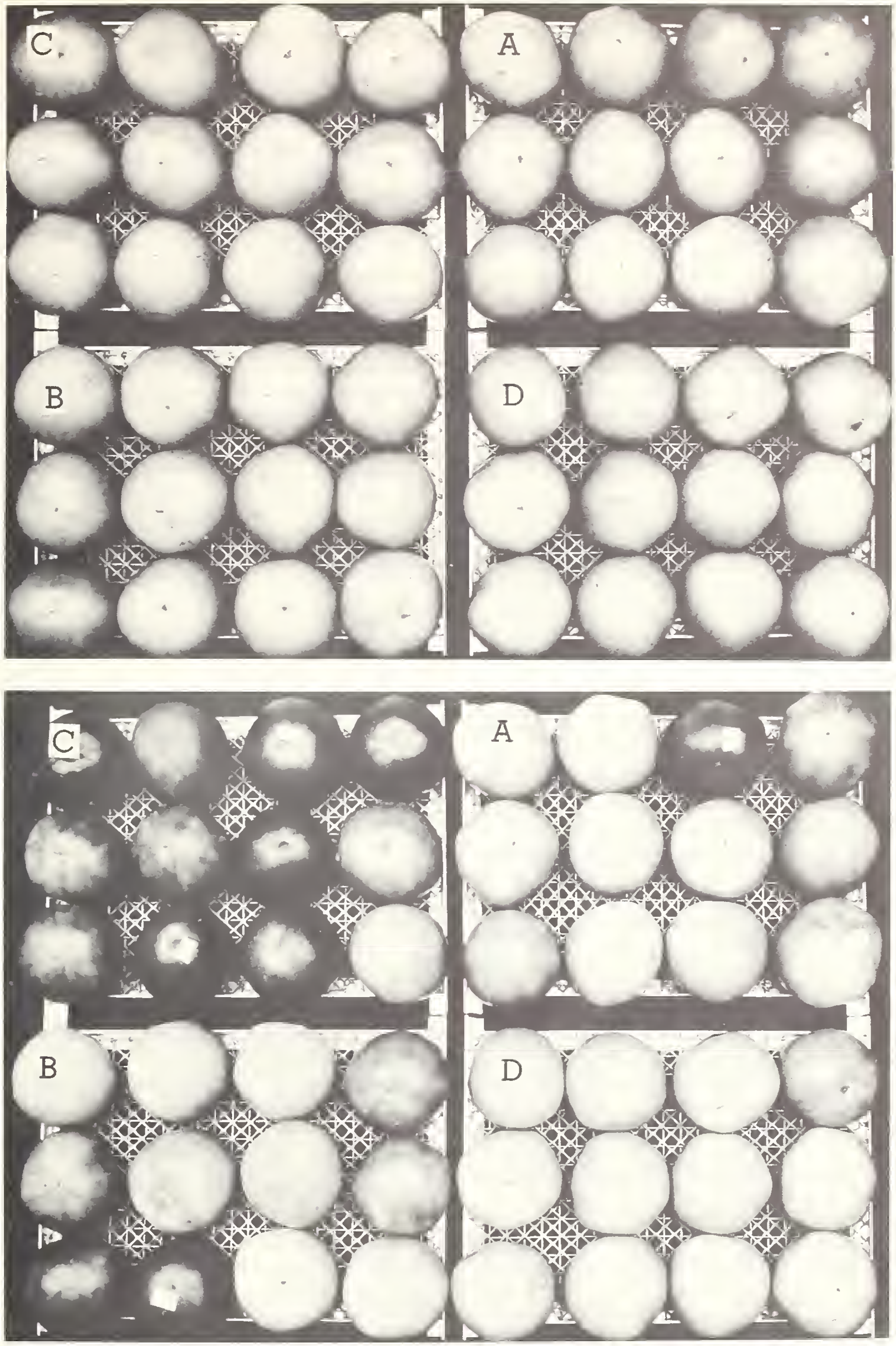

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FIGURE 3.—Size, form, and maturity of tomatoes held at 21 percent oxygen in series I tests: *Top*, pretreatment appearance of second replication; *bottom*, posttreatment appearance of same fruits after storage for 12 days at 65° F. [C=755 mm. of Hg, B=570 mm., A=380 mm., D=190 mm.]

become 67.4, 64.1, 62.3, and 39.8. All the stored fruits appeared to ripen normally at 70° regardless of the pressure at which they previously were stored. However, after 3 days at 70° following storage, the lots previously stored at 190 mm. of Hg still showed marked retardation of ripening compared with those stored at 755 mm. of Hg.

The tests reported here were without supplementary humidification of the fruits during the hypobaric storage periods. The fruits lost weight in each treatment, as shown in table 2. The mean percent loss in series I was C, 3.5; B, 4.8; A, 5.4; and D, 7.3. These losses are significantly different at the 1-percent level. They closely approximated a 1° regression on the hypobaric pressures. There was a tendency toward greater weight loss at the back of the hypobaric chambers, but this difference was not significant at the 5-percent level.

Series II Tests

For the series II tests, slightly smaller tomatoes were used that still met the uniformity standards chosen as minimums. There also was a slightly greater variability in the initial fruit weights within treatments. The mean weight was 146.6 grams each, with coefficients of variation within treatments from 4.8 to 6.5 percent. However, the coefficient among treatments was only 0.12 percent, and there was no significant difference at the 1-percent level among the initial weights of fruits in any one treatment over those in any other treatment.

There also was greater variability in the initial maturity of fruits in this series, with coefficients from 10.7 to 14.1 percent within treatments. Fortunately, however, there was a zero coefficient of variance among treatments. The results reported were for the less favorable of the two replications. It is these tomatoes that are shown in figure 4 (top). All pretreatment maturity scores were estimates of the internal color of the fruits as indicated by the multiple wavelength difference meter, which measures light transmittance, and were not based on any external color. All these fruits appeared uniformly mature green.

The posttreatment maturity of this series also was evaluated by the multiple wavelength meter, and the results were statistically compared. The method chosen was the difference in internal color developed between the measurements when the treatments were begun and when they were terminated. Internal and external color development, as in series I, showed good correlation. These fruits after storage for 28 days at 65° F. in the chambers are shown in figure 4 (bottom).

An analysis of variance of these maturity scores showed a significant variation within treatments, as one might expect from the external color differences shown in figure 4. However, there was no apparent difference among treatment effects. At the end of storage the amount of ripening in each treatment was similar. The *F*-value for variance among treatments was 0.21, whereas the *F*-value required for significance at even the 5-percent level was 2.82.

As in series I, the fruits lost weight during storage in each series II treatment (table 2). The mean percent loss was C, 9.3; B, 8.8; A, 11; and D, 14.4 (table 2). Thus there was a trend of increasing weight loss with increasing vacuum about the fruits, but in this replication it was not significant at the 5-percent level.

TABLE 2.—*Weight loss and color gain of tomatoes during storage at 65°±3° F. in test series I and II at various hypobaric pressures*

[48 tomatoes in each series]

Hypobaric pressure (mm. Hg)	Series I (constant oxygen percent for 12 days)		Series II (constant oxygen pressure for 28 days [2])	
	Weight loss	Color gain [1]	Weight loss	Color gain [1]
	Percent	*Percent*	*Percent*	*Percent*
755	3.5	146.8	9.3	57.1
570	4.8	107.0		
545			8.8	63.8
380	5.4	77.4	11.0	64.2
190	7.3	49.9		
180			14.4	62.0

[1] Internal color development, as measured by multiple wavelength difference meter. At 5-percent level, color gains were significantly different in series I but not in series II.

[2] At 12 days all series II tomatoes had about same external color as those in series I stored at 190 mm. of Hg.

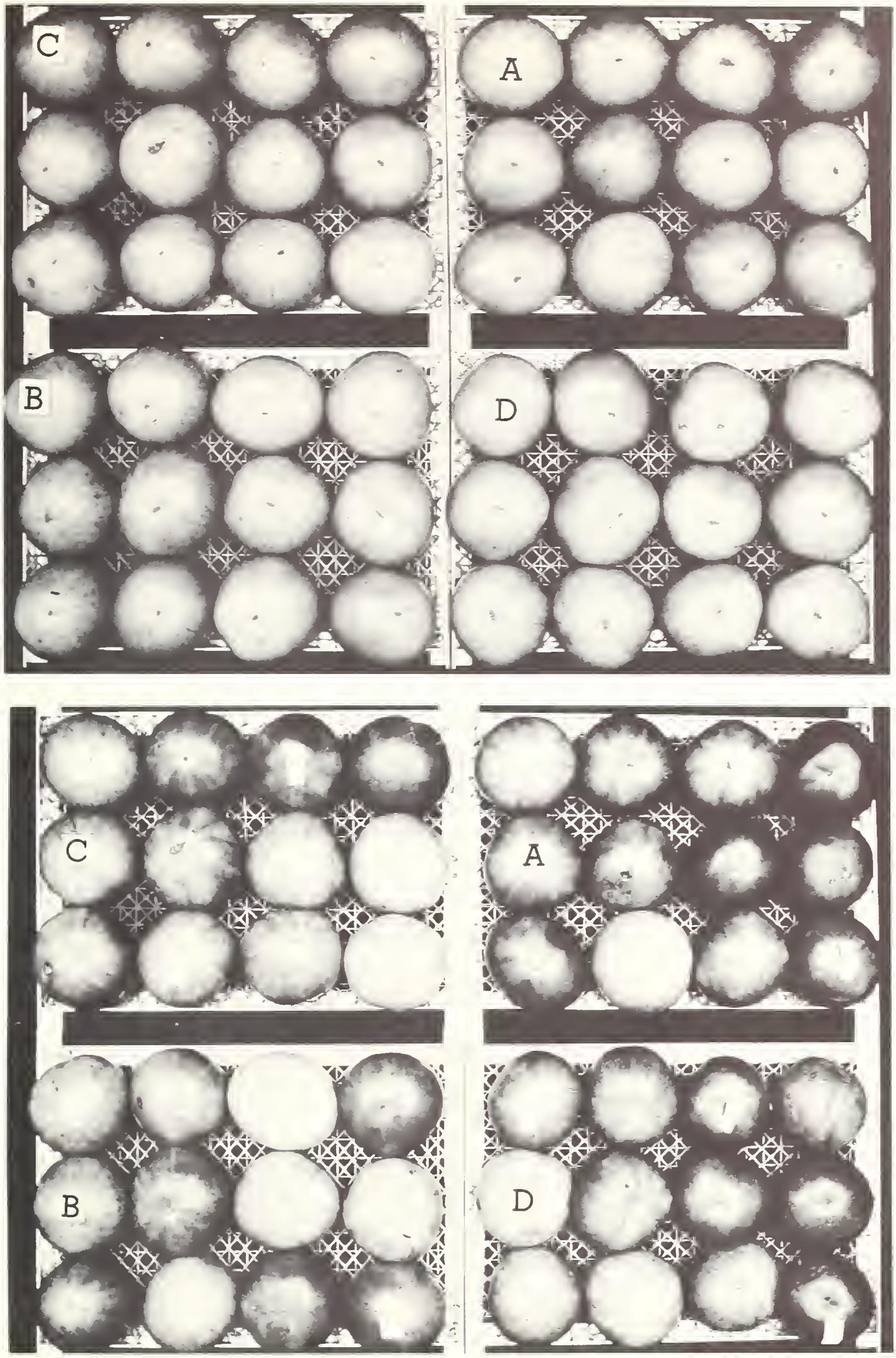

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FIGURE 4.—Size, form, and maturity of tomatoes held at 38 mm. oxygen partial pressure in series II tests: *Top*, pretreatment appearance of second replication; *bottom*, posttreatment appearance of same fruits after storage for 28 days at 65° F. [C=755 mm. of Hg, B=545 mm., A=380 mm., D=180 mm.]

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Discussion

Literature on the possibilities of hypobaric storage of fruits and vegetables, with few exceptions, has been limited to laboratory observations (*8*, *20*). Few if any suggestions have been made for commercial applications of hypobaric storage. The results reported here suggest that much research remains to be done. There should be no inference that hypobaric storage can succeed without supplementary refrigeration nor that any produce other than top quality might be so stored.

These tests, and others in progress, indicate that hypobaric equipment needs to be automated as much as possible and that humidification under vacuum conditions must be provided. Rates of flow for the sweep gas through the hypobaric chambers have not been sufficiently studied for recommendations. These may need specification not only for economy but also because rates of flow considerably affect the amount of water lost by the produce. Actual data on water losses from different kinds of produce held under comparable conditions are meager (*23*, *24*). If 5 to 10 percent of the water is lost, shriveling usually occurs (*11*). Water losses also may affect the diffusion of gases from produce (*32*).

Hypobaric storage requires a sufficient flow of oxygen into the chamber to sustain aerobic respiration of the produce. Most information on respiration requirements for produce is incomplete. More information is needed on tolerances to various low-oxygen atmospheres. Also, the sweep gas in a hypobaric system may need to reduce ethylene accumulations to as little as 0.1 p.p.m. (*1*, *7*). From these considerations, a single rate of flow adequate for all produce appears unlikely.

The appearance of the tomato fruits before and after storage in chambers with various pressures (figs. 3 and 4), plus objective measurements of their maturity and color development, indicates that the effects of hypobaric storage may be more directly associated with oxygen levels maintained than with the removal of ethylene. (See also *18*, *22*, *27*.)

Hypobaric treatment C at 755 mm. of Hg in series I did not lengthen the storage period or appreciably retard ripening over that of fruit held in an adjacent room at the same temperature but at atmospheric pressure. These latter fruits were not so carefully selected as those in the chambers, but they were from the same lot and were approximately the same size.

It is known that even small amounts of carbon dioxide are sufficient to overcome the ripening effects of ethylene at room temperatures (*7*, *10*). Thus, for testing the physiological effects of ethylene, the continued use of hydrated lime packets or other suitable carbon dioxide absorbents within storage chambers seems advisable. Gas supplies also must be free of carbon dioxide content.

Hazards may be present in some aspects of work with vacuum chambers and reduced pressures, and work efforts should be guided accordingly (*2*, *16*, *31*, *36*).

Additional experiments are in progress using the equipment described here. Hopefully, additional data will clarify the merits of hypobaric storage. From these preliminary observations, it would appear that the hypobaric storage method may have some merit. However, equipment costs may be high. Auxiliary uses of hypobaric storage and its future possibilities may extend to decay control, ethylene removal, and perhaps other horticultural crops (*3*, *12*, *15*, *17*, *19*, *21*, *29*, *35*).

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U.S. GOVERNMENT PRINTING OFFICE: 1969 O—336-991

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